Article Title:

Multi-temporal Analysis of Underbody Improvised Explosive Device (IED) Theater Events on Ground Vehicles moving in a Convoy using Modeling and Simulation (M&S)

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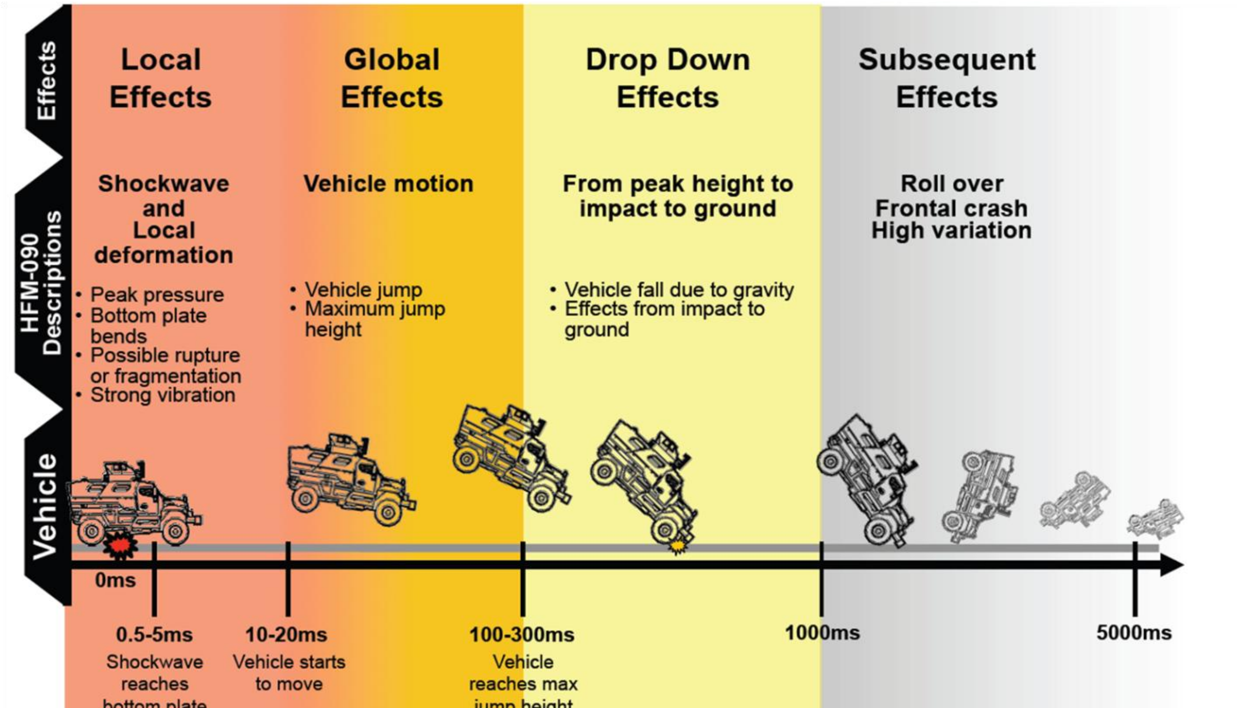
Abstract of article:

In the past few years, modeling and simulation (M&S) engineers have made impressive strides in their ability to improve ground vehicle reliability and Soldier safety. A recent physics-based, computational study called “Blast-on-the-Move” conducted by a TARDEC team epitomizes the steady progress in M&S capabilities applicable to defense acquisition. Typically, live-fire testing and evaluation (LFT&E) focuses on the effects of underbody blasts on a stationary vehicle. This research on the effects of a blast on moving vehicles was awarded the 2012 Army Materiel Command (AMC) Systems Analysis award.

Body:

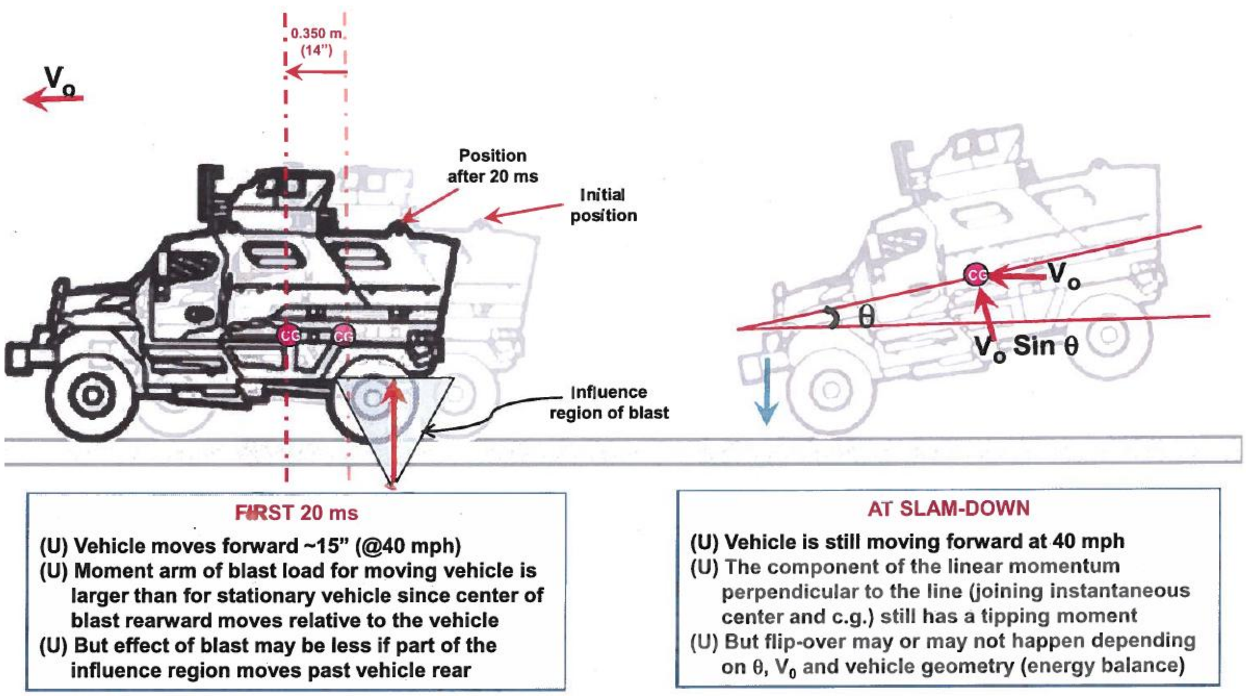
During the period October 2011 – April 2012, the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) team dedicated significant time and effort toward deeper analysis and understanding on the dynamics of the underbody IED blast events on moving ground vehicles (also called “Blast on the Move”). In its effort to support the analysis, a multi-fidelity, multi-temporal M&S methodology was developed and successfully applied towards reconstruction of theater IED events.

An IED blast event from blast-off to return to ground (RTG) lasts for about 500-2500 milliseconds (ms) depending on the vehicle, threat and threat location. Since occupant injuries can happen in both stages (blast-off and RTG) of the event, it is imperative to analyze both of them in a multi-temporal fashion. For a successful analysis of such an event, innovative computational modeling is essential in understanding underbody blast effects on a moving vehicle structure and its occupants because it provides in-depth information on the overall physics of the event, with access to tremendous amounts of data and visualization.



Definition of Blast Event (NATO HFM-090) (Ref 2)

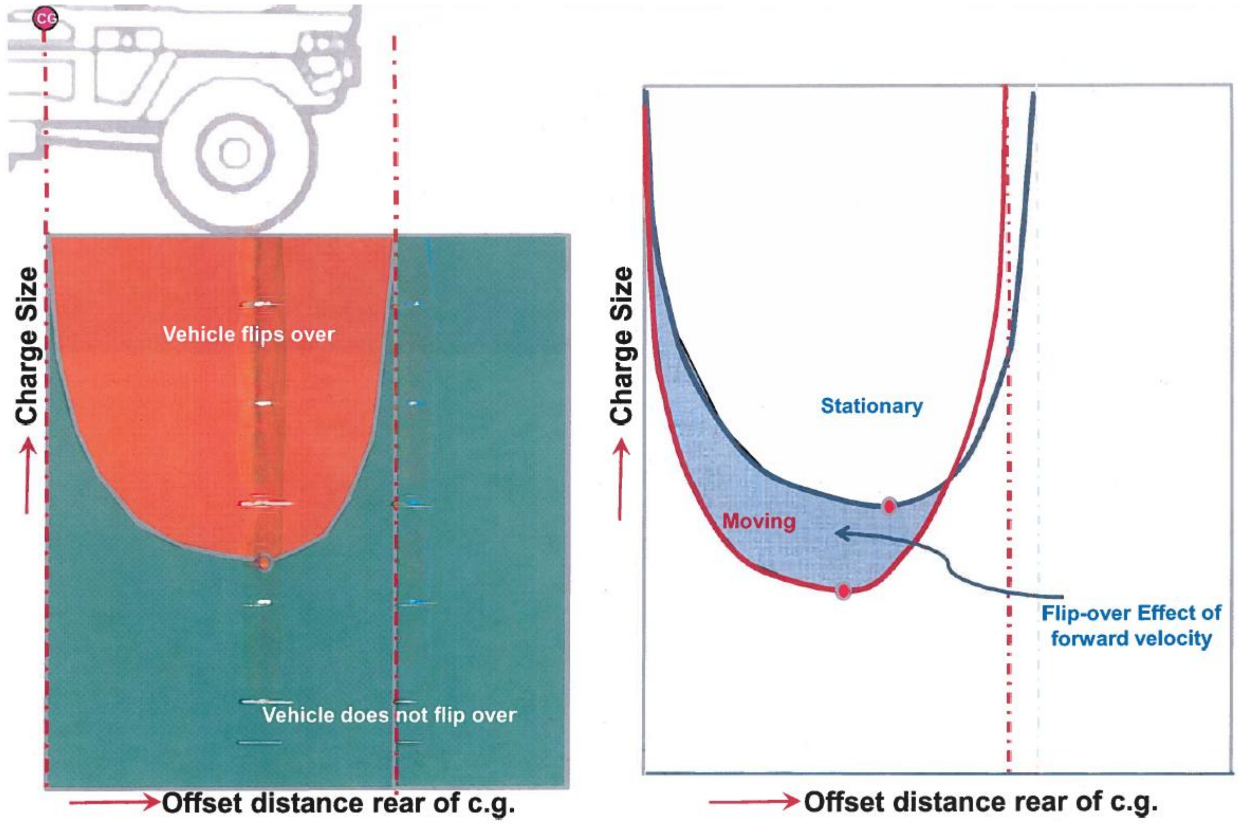
Theater IED events involving vehicles moving in a convoy have always sparked considerable concern because the effects of IEDs are seemingly accentuated by the vehicle's forward velocity, especially as it pertains to vehicle flip-overs and rollovers. This has been a hotly discussed topic among the blast T&E (Test and Evaluation) and ground vehicle survivability community - All Live-Fire testing and Evaluation (LFT&E) has been done to date on stationary vehicles while the majority of the blast events in theater operations occur on moving vehicles. The team took the initiative in developing a computational methodology to be able to analyze vehicle performance not only during the blastoff phase but through the entire event (blastoff through return to ground). In doing so, the team was able to do an operational evaluation of vehicles moving at different velocities when subjected to an underbody blast.



The TARDEC team developed a two-phased, multi-temporal strategy in which a high-fidelity M&S model was used to simulate the blast-off phase, and a Reduced Order Model (ROM) was utilized to capture the vehicle free flight phase including vehicle flip-overs. In the first phase of the analysis, the team used high fidelity models including detailed vehicle structures along with occupants and analyzed the effects of the vehicle's forward velocity during blast-off. This model captured the complex phenomena that occur during this very brief time, namely, the interaction between the charge's detonation, soil, air and the vehicle's underbody. The vehicle structural performance including hull and floor deformations and occupant injury responses were analyzed.

Using the same high-fidelity approach from the first blast-off phase for the longer second phase is a prohibitively expensive and a time-consuming proposition from a computational viewpoint, even when executed on the TARDEC's High Performance supercomputers. Therefore, for the second phase of the analysis, the team utilized a Reduced Order Model to simulate the vehicle free flight until RTG. The innovative manner in which the geometry as well as the blast loading were modeled to a reduced order and yet obtain accurate predictions of vehicle global behavior in a timely manner is critical to the success of this methodology.

During this second phase, the vehicle's flip-over tendencies and the effect of forward velocity on these flip-overs were analyzed in detail. The team has also introduced the concept of "flip-over characteristic curves" which are vehicle-specific descriptors of the combinations of the three variables (speed, charge size and charge offset) that will flip the vehicle over in an underbody blast. For example, in the left figure below, the red region conceptually represents the combinations of charge size and offset that will result in a vehicle flipping over when moving at a certain speed. On the right figure below, the region shaded between the two curves shows the effects of forward velocity. This region represents scenarios where, the same charge size and center-of-gravity (c.g.) offset will result in a moving vehicle being flipped over, but not the same vehicle when stationary.



The benefits of this methodology are far-reaching and significant. Indeed, in some areas, successful application of this methodology is already in progress and described below:

- Theater Reconstruction: Previously, theater reconstruction analysis involved primarily the structural damage observed during the blast-off phase, such as impact location, deformation, breach, etc. Now, it is also possible to consider the longer-term vehicle kinematic observations in event storyboard reports such as rollover/flip-over to reconstruct the IED event.

  The TARDEC team has effectively applied this analysis strategy in the reconstruction of a recent theater IED blast event. Using these tools, the team estimated the Net Explosive Weight (NEW) of the Home-made-explosives (HME) for a recent Stryker theater event and presented the findings to the Intelligence and Survivability community of practice at the National Ground Intelligence Center (NGIC) meeting. The TARDEC team will continue to apply this analysis methodology in reconstructing other theater events for vehicles such as Mine Resistant Ambush Protected (MRAP) and MATV (MRAP All-terrain Vehicle).

- Standards and Specifications: For forward-looking Science and Technology (S&T) programs such as the Occupant-Centric Platform (OCP) Technology-Enabled Capability

Demonstrator (TECD) project, such analyses provides insight into whether testing with moving vehicles should be recommended as part of the LFT&E protocol.

Additionally, the flip-over characteristic curve described earlier should be highly relevant as new design standards are evaluated for future consideration in acquisition programs.

- Product Development: The methodology is invaluable during the design development, fielding and sustainment phases of both the wheeled and tracked vehicles; firstly, as a toolset to help meet any specification related to characteristic curves, and secondly, in the design of *active* countermeasures to keep the vehicle from flipping over once the tendency to do so is sensed by onboard sensors.
- Testing and Evaluation (T&E): A new Blast on the Move test range is currently being stood up in Aberdeen Proving Grounds (APG), Maryland, and this M&S capability can be used to help design the test and vehicle setup to get the most useful information out of the tests. LFT&E tests and especially Blast on the Move tests are expensive, and this analysis has the potential to reduce Army testing and evaluation costs significantly. This will also enable faster turnaround of many parametric design and sensitivity studies of various operational excursions, which are too numerous to test individually. Thus, by supplementing the physical testing, the overall evaluation of vehicle performance is enhanced.

In summary, with this analysis capability, the Army has the computational M&S capability to design superior vehicle systems for better crew survivability with reduced test costs to protect Soldiers from the ever-increasing threats of landmine blasts.

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Brief Biographies of each author:

Dr. Thyagarajan received his B.S. in Mechanical Engineering from the Indian Institute of Technology-Madras, and his M.S. and Ph.D. in Applied Mechanics from the California Institute of Technology, Pasadena. His doctoral dissertation was on the Modeling and Analysis of Hysteretic Structural Behavior. He spent over 15 years in the automotive industry at Ford Motor Company and Visteon Corporation, where he was involved in all aspects of product development of automotive interiors. His automotive experience includes leadership roles in concept-to-launch product design, human factors/ergonomics development, as well as in the standardized application of computer aided engineering tools during the overall design engineering process. He has two patents, written over 30 technical papers and is co-organizer of Society of Automotive Engineers (SAE) Congress sessions. Dr. Thyagarajan now works as a R&D staff member at US Army TARDEC in the M&S of underbody mine blasts and automotive crashworthiness applications. He received the Army Materiel Command (AMC) Systems Analysis awards in 2010 and 2012, and in 2012, was appointed by the TARDEC Research Reviewer Board as a Senior Technical Specialist. He is also a member of the Army Acquisition Corps. Recently, he received the Forest R. McFarland Award at the 2013 SAE World Congress.

Mr. Jai Ramalingam received his B.E. degree in Mechanical Engineering from PSG College of Technology, India, and M.S. degree in Mechanical Engineering from Southern Illinois University at Carbondale. His post-graduate research focus at Florida State University was in the mechanical characterization of ceramics and composites and micro-mechanical material modeling. As a safety consulting engineer at Ford Motor Company, Mr. Ramalingam worked on many of the early safety projects relating to evaluation of Advanced Safety Restraint Systems to enhance occupant protection. Later at Chrysler, his focus was in automotive crashworthiness, focusing on full vehicle side, frontal and rear impact events, and using evolving M&S methodologies to meet FMVSS regulations and obtain star-rating targets. Mr. Ramalingam now works at TARDEC performing underbody blast simulation analysis and developing/evaluating countermeasures and mitigation technologies to improve soldier survivability. He received the Army Greatest Invention award in 2009 and AMC Systems Analysis awards in 2010 and 2012. In 2012, he was also honored with the Achievement Award for Civilian Service.

Mr. Sanjay Kankanalapalli joined TARDEC in 2009 and is currently working in the Analytics group as an Energetic Effects and Crew Safety Modeling and Simulation engineer. He specializes in modeling ground vehicle structures and studying the interaction effects between vehicles and occupants during blast and crash events, and has published several reports on the same. He has over 15 years experience at Chrysler and Ford Motor Company, in the area of crashworthiness and vehicle safety simulations. He has a B.S. degree in Mechanical Engineering from Andhra University, India and an M.S. degree in Mechanical Engineering from Wayne State University. He received the Army Greatest Invention award in 2009 and AMC Systems Analysis awards in 2010 and 2012. In 2012, he was also honored with the Achievement Award for Civilian Service.

Mr. Vunnam received his M.S. degree in Mechanical Engineering in 1993 from Wayne State University. He worked at GM and Chrysler as on site Project Engineer, mainly involved in developing crash safety and restraints models and methodologies to assess occupant injury risk in vehicle crash tests. Later, he moved to Ford Motor Company as Product Development Engineer and worked in North American Car and Truck Safety organizations. His experience at Ford includes developing vehicle crash safety models to evaluate the performance of vehicles for occupant safety. After joining TARDEC, Mr. Vunnam spearheaded several underbody blast M&S projects included working in a technical team for the development of End2End system level computational Underbody mine blast modeling and simulation framework. Mr. Vunnam currently serves as Team Leader for Energetic Effects and Crew Safety M&S Team in the Analytics Department. He is responsible for planning, directing, reviewing, and coordinating efforts of personnel engaged in research, development, and engineering. In addition to team leadership, which involves administrative and resource management, he is also focused on technical strategy, project management, and meeting customer deliverables and satisfaction with the highest standards. He received Army Greatest Invention award in 2009 and AMC Systems Analysis awards in 2012.